

*Citation for published version:*

Zografou, A, Heath, A & Walker, PJ 2014, 'China clay waste as aggregate in AA cement mortars', *Proceedings of the Institution of Civil Engineers: Construction Materials*, pp. 1-11. <https://doi.org/10.1680/coma.13.00037>

*DOI:*

[10.1680/coma.13.00037](https://doi.org/10.1680/coma.13.00037)

*Publication date:*

2014

*Document Version*

Publisher's PDF, also known as Version of record

[Link to publication](#)

## University of Bath

### Alternative formats

If you require this document in an alternative format, please contact:  
[openaccess@bath.ac.uk](mailto:openaccess@bath.ac.uk)

#### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

#### Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# China clay waste as aggregate in alkali-activated cement mortars

**Adamantia Zografou** MSc

PhD student, Department of Architecture and Civil Engineering, University of Bath, Bath, UK

**Andrew Heath** MS, PhD, FHEA

Senior Lecturer, BRE Centre for Innovative Construction Materials,

Department of Architecture and Civil Engineering, University of Bath, Bath, UK

**Pete Walker** PhD, CEng, CPEng, MICE, MIEAust

Professor, BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, Bath, UK

**Every 1 t of china clay produced in the UK generates 9 t of waste material. A limited quantity of the coarser waste has beneficial use as a building stone or secondary aggregate in concrete and asphalt, but there are currently limited uses for the finest waste fraction. 'Mica' waste is a mixture of fine minerals and is one of the forms of waste with little beneficial use other than the restoration of old quarries. With an aim to find new commercially viable and low environmental impact uses in construction, this paper focuses on the use of china clay waste as an aggregate in alkali-activated cement mortar. Based on preliminary analysis of the compressive strength of binders using slag and fly ash, optimum binders were selected to produce mortars using mica and other forms of china clay waste as aggregate. The mortars were then compared in compression with control specimens using standard sand. Although the results show that the test mortars were generally weaker than the control samples, the paper concludes there are opportunities for their use.**

## 1. Introduction

For every 1 t of china clay (almost pure kaolin) produced in the UK, approximately 9 t of waste is generated (Thurlow, 2005). The production of china clay and its associated waste have permanently altered the landscape in parts of Cornwall. Based on the UK production of approximately 1 Mt a year (Brown *et al.*, 2012), this equates to an annual waste quantity of approximately 9 Mt, which is well below the UK primary aggregate use of approximately 145 Mt (BGS, 2013).

There are three main forms of china clay waste: stent, which is coarse, unaltered granite with a dia. of up to 2 m; sand, which derives from the same rock and is fragmented due to weathering and crushing; and mica, the finest waste fraction with particle size just above 0.5 mm. Surprisingly with its name, the latter does not comprise pure mica, but actually contains less than 10% mica flakes along with other minerals (predominantly quartz). The current waste streams are composed of approximately 50% stent, 39% sand and 11% mica.

Less than 20% of the live feed waste production of stent and sand is sold to commercial enterprises, who make 'secondary aggregates' out of it for applications as ready-mixed concrete, in asphalt bases and surface courses, in precast concrete products and as plain aggregates for fills, capping, in hydraulically bound and unbound mixtures (Thurlow, 2005). This percentage could be increased if the cost and environmental impact of transport

to more distant markets could be reduced. About 70% of aggregates used in Cornwall for road construction are derived from china clay pits. Previous investigation on the alkali-silica reactivity of china clay stent from Littlejohn quarry in Cornwall showed 'low reactivity by BRE Digest 330 classification' (Marsh, 2006).

The 'mica' waste stream currently has little beneficial use and is generally utilised for backfilling mines. Because of the large quantities of this material that are produced, it was determined that a bulk use in building products should be investigated. This material has the advantage that high-energy crushing is not required before use as an aggregate, should it be suitable for this use, but the fine grading means that it does not meet current specifications for sands in cementitious mixes.

As part of the Cornwall eco-town development near St Austell, a desire to develop construction materials based on the china clay waste was expressed. It was intended that these should be used in the construction of low-impact dwellings in the area, and a potential bulk use of the waste as an aggregate in cement-bound construction materials (blocks and roofing tiles) was identified. Rather than only investigating the use of the waste with Portland cement (PC) binders, the use of the china clay waste with potentially lower impact alkali-activated (AA) binders was investigated. AA binders or geopolymers were identified by the Intergovernmental Panel on Climate Change (IPCC) as one of two feasible alternative binders which could

produce a significant reduction in the global carbon dioxide emissions from cement manufacture (Metz, 2007).

Before embarking on a detailed investigation of the use of china clay waste in bound construction materials, the waste was characterised along with potential additives, notably ground granulated blast furnace slag (GGBS), fly ash (FA) and PC.

## 2. China clay waste

### 2.1. Available forms

The waste used in this study was obtained from Imerys Minerals Ltd in Cornwall. Two forms of the waste are used in this paper: mica waste (M) and china clay sand (CCS), which is commercially available as a secondary aggregate. The mineralogy of the waste differs slightly between the different forms and also may vary from batch to batch. It generally comprises five minerals: quartz, feldspar, schorl, mica mineral and leftover (non-recovered) kaolinite as shown in Table 1. An X-ray fluorescence (XRF) analysis indicating the oxide composition is shown in Table 2 and the particle size distribution of the mica waste is illustrated in Figure 1, along with the particle size distribution for a standard mortar sand in EN 196-1 (BSI, 2005a). Although the particle size distribution of the CCS can be altered in the plants in which it is processed, Figure 1 presents the particle size distribution for the CCS used in this study.

Mica is a family of minerals. More specifically the mica mineral present in this waste stream consists mainly of muscovite with some biotite and zinnwaldite. According to BS EN 1097-6 (BSI, 2013a), clause 9, the apparent particle density of this fine waste is  $2.71 \text{ mg/m}^3$  and the water absorption is 1.5%, while standard siliceous sand conforming to BS EN 196-1 is estimated to have apparent particle density and water absorption of  $2.62 \text{ mg/m}^3$  and 0.5% respectively.

### 2.2 Technical specifications for use as aggregate

China clay sand does not require extensive modification to conform to BS EN 12620 (BSI, 2002) Grade 0/4 (MP) due to its manufacturing process and is suitable for use in concrete as it has low silt content (Wrap, 2004). In addition, concrete formed

Constituents: wt%	M	CCS
Silicon dioxide	81.23	84.30
Aluminium oxide	10.95	9.20
Potassium oxide	3.21	3.11
Iron (III) oxide	1.89	1.58
Magnesium oxide	0.32	0.23
Sodium oxide	0.29	0.32
Titanium dioxide	0.22	0.14
Calcium oxide	0.05	0.05
Loss on ignition	1.79	1.03

**Table 2.** Chemical analysis of waste by X-ray fluorescence

using stent or CCS conforms to BS 8500 (BSI, 2006) and BS EN 206-1 (BSI, 2013b; Marsh, 2007). Because it is a plentiful secondary aggregate, CCS is low in cost. It is immune to alkali-silica reaction (ASR) and the thaumasite form of sulfate attack (TSA). It does, however, need a higher water content in concrete mixes because of the mica mineral present, which can split into very thin flakes because of the perfect cleavage parallel to the basal plane of the mica crystal. This increases the surface area of the fine aggregate and results in an increase in the water demand of the concrete. Hence, for a given concrete strength and compared to other standard sands, the concrete mix with CCS needs higher cement content. To overcome this issue CCS may be blended with high-quality sand from natural land-based sand deposits or washed marine sand. This cost can be offset by the low cost of the material, which is exempt from the aggregates levy (Wrap, 2004).

In *Lea's Chemistry of Cement and Concrete* (Sims and Brown, 2003) muscovite and biotite micas are described as having 'disadvantageous effects' when used in fine aggregate.

When mica occurs as discrete (or 'free') flaky grains in fine aggregates, it usually increases the water demand of concrete and also reduces the cohesiveness of the mix, which can adversely affect the final strength and durability of the hardened concrete (Sims and Brown, 2003).

Dewar (1963) studied granite-derived sands from southwest England and reported that for a typical concrete mix the compressive strength might be decreased up to 5% for presence of 1% by weight muscovite mica in the total aggregate. A study by Fookes and Revie (1982) demonstrated the impact of mica on strength, workability and water-to-cement (w/c) ratio in PC concrete; for mixes of constant workability, the compressive strength reduces by approximately 45% on the 28th day if 6% of total aggregate (an equivalent of 18% in fine aggregate) is replaced by mica minerals.

Constituents: wt%	M	CCS
Kaolinite	8	4
Mica	9	9
Quartz	50	58
Feldspar	22	21
Schorl	11	8

**Table 1.** Mineralogical analysis by X-ray diffraction

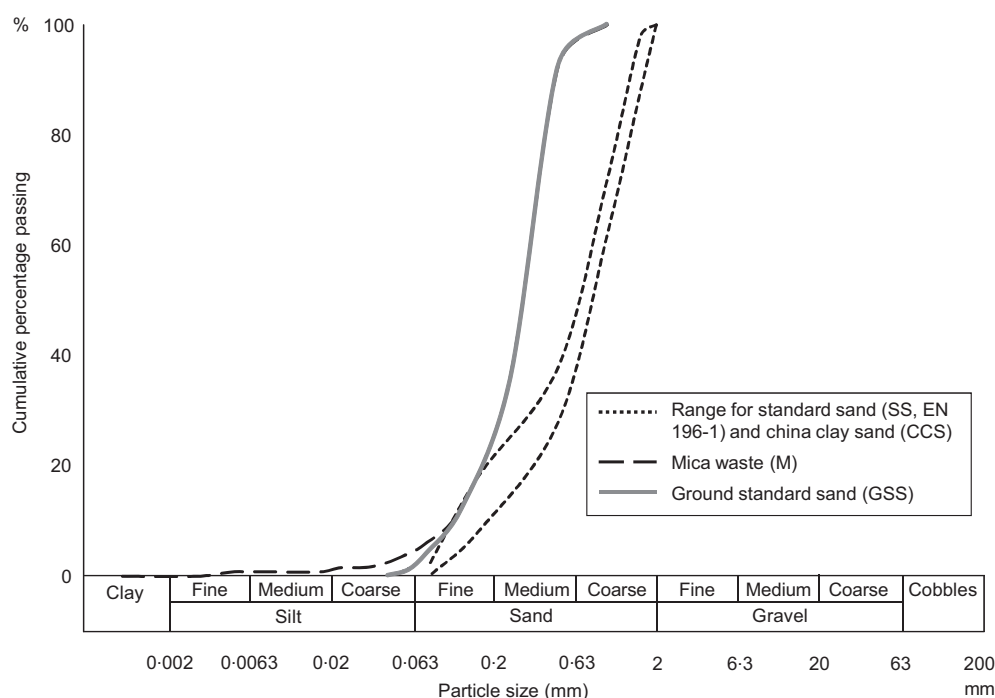


Figure 1. Particle size distribution of the types of sand used

This previous work did not distinguish between the effect of changing particle size distribution and the effect of adding mica mineral, and the study was also focused only on using mica mineral in PC-based concretes. It did, however, indicate that the ‘mica’ waste stream has potential to be used as a fine aggregate in mortars, but that this may lead to reduced strengths. The current work has attempted to quantify the effect of particle size distribution as well as mica content on the performance of both PC and AA binder mortars. The behaviour between PC and AA may be different for two main reasons.

- PC-based mortars require water for hardening reactions, whereas AA geopolymers require water for dissolution but can produce water during hardening (Duxson *et al.*, 2007). As noted earlier, the addition of mica affects the water demand of the mix, which could therefore affect the hardening of the different binders in different ways.
- Micaceous minerals are an aluminosilicate mineral, which could affect the aluminium-to-silicon (Al: Si) ratio in the AA materials and thereby affect their strength (Davidovits, 2011). Although the micaceous minerals were not converted to a dehydroxylated state through calcination, there is still some dissolution of micaceous minerals under alkaline conditions and this is affected by temperature, dissolved aluminium and pH (Oelkers *et al.*, 2008).

### 3. Experimental work

A series of tests was undertaken to determine how the waste performs as an aggregate in PC and AA binders.

#### 3.1 Materials

Two series of AA mortars were produced: one based on FA and one on GGBS, and these were compared to a control based on PC. The samples were tested in compression after 7, 28, 90 and 180 d of curing.

##### 3.1.1 Ground granulated blast furnace slag

Ground granulated blast furnace slag (GGBS) was provided by the Hanson Heidelberg cement group from the Port Talbot works. Its chemical analysis is shown in Table 3. In the X-ray diffraction analysis (XRD) pattern (Figure 2), the halo and the absence of distinct peaks which would correspond to impurities indicate it is highly amorphous, unlike the FA which showed distinct peaks (Figure 3), as discussed in the following subsection.

##### 3.1.2 FA

Cemex 450-S was the type of FA used in the tests and its chemical composition is shown in Table 3. An XRD analysis (Figure 3) showed distinct peaks for quartz, mullite and haematite in addition to the amorphous materials.

Constituents: wt%	GGBS	FA
Silicon dioxide	35.15	49.00
Aluminium oxide	13.07	23.50
Iron (III) oxide	0.28	8.70
Calcium oxide	39.60	2.40
Magnesium oxide	8.47	1.40
Sulfur trioxide	0.17	0.80
Sodium oxide	0.14	3.06
Potassium oxide	0.51	0.87
Titanium dioxide	0.66	
Manganese oxide	0.44	
Phosphorus pentoxide		1.10
Loss on ignition	0.97	4.40

**Table 3.** Chemical analysis of precursors by X-ray fluorescence

### 3.1.3 Sodium silicate and sodium hydroxide

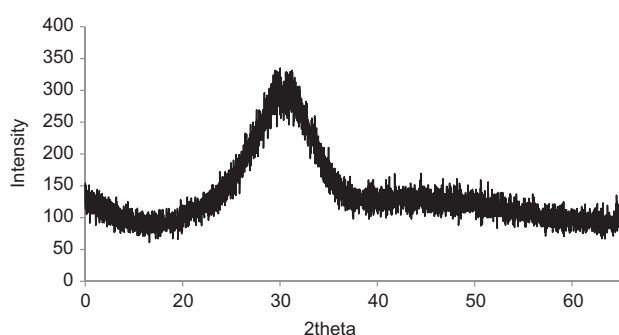
The sodium silicate ( $\text{Na}_2\text{O} \cdot n\text{SiO}_2$ ) used for the research was supplied by Tennants Distribution Ltd. It was in solid (spray-dried powder) form and comprised sodium oxide ( $\text{Na}_2\text{O}$ ), silicon dioxide ( $\text{SiO}_2$ ) and water ( $\text{H}_2\text{O}$ ) at 27.05, 53.5 and 19.45 wt% respectively. Dry sodium hydroxide ( $\text{NaOH}$ ) pellets were used and both these and the sodium silicate ( $\text{Na}_2\text{O} \cdot n\text{SiO}_2$ ) were mixed with distilled water and cooled before use.

### 3.1.4 PC

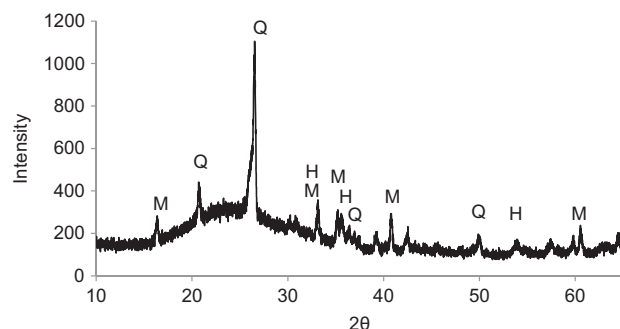
Portland cement mortars were produced for comparison. In order to achieve high strength, comparable to the strength of the AA cement mortars, CEM I 52.5N by Cemex was used. This is a PC that is free of mineral additives, which was chosen in order to minimise the effect of mineral additives.

### 3.1.5 Sand

Clause 5.1 EN standard 196-1 (BSI, 2005a) specifies that a standard sand (SS) for production of mortars contains at least 98% silica and has a particle size distribution with maximum



**Figure 2.** XRD pattern of GGBS



**Figure 3.** XRD pattern of FA (Q: quartz, H: haematite, M: mullite)

2% passing the 0.08 mm sieve, as shown in Figure 1. This SS was used in the testing.

The effect of particle size distribution was assessed through comparing mixes using aggregates of equivalent particle size: SS with at least 98% silica was ground and sieved (ground standard sand (GSS)) to have approximately the same particle size distribution of M, and the coarser waste sand from the china clay extraction (CCS) was prepared to the same particle size distribution as the SS (Figure 1). By reducing the role of particle size through materials with the same particle size distribution, the effect of sand mineralogy can be assessed.

## 3.2 Scanning electron microscopy (SEM)

A Jeol SEM6480LV was used for imaging the AA mortars after 6 months of curing. All samples are fragments stored in a desiccator before imaging and were tested in a low vacuum. For that reason the samples were not coated.

## 3.3 Procedures for the preparation of samples

As there are no EN standard procedures for the preparation of geopolymers, the following were used.

### 3.3.1 Composition of the binder

For the production of the AA binders, the sodium hydroxide and sodium silicate solutions were prepared separately and left to cool before use. For the slag-based series, the synthesis of the solution can be expressed as  $1\text{Na}_2\text{O}:1.25\text{SiO}_2:35.90\text{H}_2\text{O}$ . After the addition of slag and assuming the dissolution is complete, the whole geopolymeric system had the composition:  $1\text{Na}_2\text{O}:7.3\text{SiO}_2:1.6\text{Al}_2\text{O}_3:35.90\text{H}_2\text{O}$ .

For the FA geopolymer series, the synthesis of the solution can be expressed as  $1\text{Na}_2\text{O}:1.0\text{SiO}_2:12.2\text{H}_2\text{O}$ . After the addition of FA and again with the assumption of full dissolution, the whole geopolymeric system had the composition:  $1\text{Na}_2\text{O}:6.6\text{SiO}_2:1.6\text{Al}_2\text{O}_3:12.2\text{H}_2\text{O}$ . In these ratios it was assumed that FA and GGBS are entirely amorphous (although

the XRD graph of FA shows some crystalline material). The silica in the ‘mica’ waste was considered non-reactive and excluded from the ratios presented above. These mix ratios were determined through an initial study where the binder strength and workability were assessed with different ratios of sodium oxide: silicon dioxide: aluminium oxide: water, and the binders selected for this study were those which produced the required strength of about 30 MPa or more while having the lowest environmental impact and therefore fulfilling the overall project aims. Because of space restrictions, the full results of this initial study are beyond the scope of this paper.

The initial setting time of the slag-based binder is 40 min and the final setting time is 50 min. For the FA-based series the initial setting time is 1 h and 45 min and the final setting time is approximately 2 h. While some studies on the potential for this material to participate in geopolymeric or pozzolanic reactions in an unprocessed and calcined form have been undertaken, the hydration kinetics of these reactions is beyond the scope of this paper.

### 3.3.2 Composition of the AA binder mortars

The composition of the mortar by mass is shown in Table 4 where ‘binder’ (B) equals GGBS or FA plus sodium oxide plus silicon dioxide (from sodium hydroxide and sodium silicate) and where ‘water’ equals the water content in the sodium hydroxide and sodium silicate, plus the total amount of water added in the mortar.

The control mortar using SS follows BS EN 196-1 (BSI, 2005a) and uses ‘binder-to-aggregate’ ratio equal to 1: 3 specified in the standard. However, all the other mixes incorporate a ‘volume factor’. This is because the finer sands have lower bulk density and fill the regular prismatic mould with less material than what is indicated in mass (g) in the standard. Table 4 shows the mix ratios including the ‘volume factors’, which results in the same mass of binder for each mould, regardless of sample density. Interestingly, although GSS and M have the same particle distribution, their different particle shape leads to different density and, consequently, different mixing ratios.

The SS control mortar specimens make minimum use of water, especially in the case of the FA series. All the other sands have greater apparent water absorption and therefore extra water had to be added to the other mixes to achieve similar workability. Even the CCS that had the same particle size distribution as the SS needed extra water, which shows the impact of particle shape and mineralogy on surface area and water absorption.

In the GGBS-based series, the SS control specimens have a water-to-binder ratio of 0.47 and the flow table test according to BS EN 1015-3 (BSI, 1999b) provided a flow of 134 mm, which is between the limits of 120 mm and 175 mm in BS EN 1015-2 (BSI, 1999a). For a water-to-binder ratio of 0.60, the mixes containing CCS and GSS had approximately the same flow ( $\pm 10$  mm). The mix using M had similar flow values of about 114 mm.

The FA series visually appeared very dry in spite of having relatively high water content. All these mixes were too dry to accurately test using the flow table, and this demonstrates the problem of transferring standard tests and mix designs developed for PC binders to alternative binders.

The full mix designs are presented in Table 5.

### 3.3.3 Mixing and curing

The separately prepared solutions were mixed for 30 s in the mixer and then the precursor was added. Mixing was first at slow speed and, after 2 min at high speed, the binder was mixed for 5 min in total. Later, sand and any extra water was added before an additional 10 min of mixing. Cylindrical moulds 36 mm high and 18 mm in dia. were used. All test results are presented as the averages of three replicates. The GGBS-based series was cured at room temperature and relative humidity (RH) >90%. The FA-based series was oven cured at 80°C until testing as the FA series did not harden under ambient conditions, as noted by Shi *et al.* (2012) for FA-based geopolymers.

Ratios of binder: water: sand			Series based on	
			GGBS/PC	FA
Aggregate type	Medium-fine	M	1: 0.65: 2.3	1: 0.55: 2.3
		GSS	1: 0.60: 2.6	1: 0.40: 2.6
	Medium-coarse	CCS	1: 0.60: 3	1: 0.50: 3
		SS	1: 0.47: 3	1: 0.27: 3

**Table 4.** Mixing ratio of mortars by weight

			Composition: g		
			GGBS series	Portland	FA series
Binders		GGBS	100·0	–	–
		FA	–	–	100·0
		Portland	–	111·0	–
		Sodium silicate powder	11·3	–	16·3
		Sodium hydroxide pellets	2·5	–	5·9
		Water added in binder	49·4	52·2	27·3
Mortars	M	Aggregate	255·4	255·4	270·7
		Extra mix water	20·0	20·0	33·0
	CCS	Aggregate	333·1	333·1	353·1
		Extra mix water	14·4	14·4	27·1
	SS	Aggregate	333·1	333·1	353·1
		Extra mix water	–	–	–
	GSS	Aggregate	288·7	288·7	306·0
		Extra mix water	14·4	14·4	15·3

Table 5. Mixing composition

### 3.4 Comparing performance with Portland cement mortars

One series of PC mortar was produced for comparison using the same sands. The binder: water: sand ratio was exactly the same as for the slag-based series in Table 4, which is close to the standard mortar mix in EN 196-1, which has a binder : water : sand ratio of 1: 0·5: 3. As with the AA binder samples, a higher water content was required to ensure similar workability for the samples with finer aggregate and with the CCS of different mineralogy, and the proportion of sand was reduced for the finer sand to account for different volume factor and to ensure the amount of binder in each sample was consistent. Mixing and curing were followed as specified in BS EN 196-1 (BSI, 2005a) but the moulds used were not the prismatic moulds specified, but the cylindrical 36 mm high and 18 mm dia. moulds used for the other mixes. PC samples were tested in compression after 7 and 28 d of curing. The initial setting time for the PC paste is 4 h and 5 min and the final setting time is 4 h and 45 min (without immersion of the sample in water, as the reference method in BS EN 196-3 (BSI, 2005b) indicates).

## 4. Results and discussion

### 4.1 GGBS mortars

The results of the compression test of the GGBS series are presented in Figure 4. As expected all samples gain strength over time.

At 7 d all samples that had a higher water content to achieve a similar workability to the SS samples had low strength compared to the SS samples. The impact of high water content decays over time as geopolymerisation continues. As a consequence, the difference in strength between the CCS mortar and the SS control mortar decreased from the initial 29·6% on day 7 to 5·2% difference by 6 months. Generally, the medium-coarse aggregates produce mortars of higher strength than the fine-medium aggregates.

Figure 5 shows images of the SS, M and CCS samples. The binder matrices in all geopolymer samples have common characteristics: highly amorphous, with a number of undissolved particles of slag and microfissures. Although it is

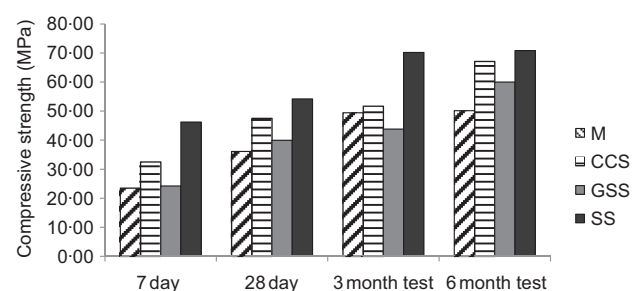
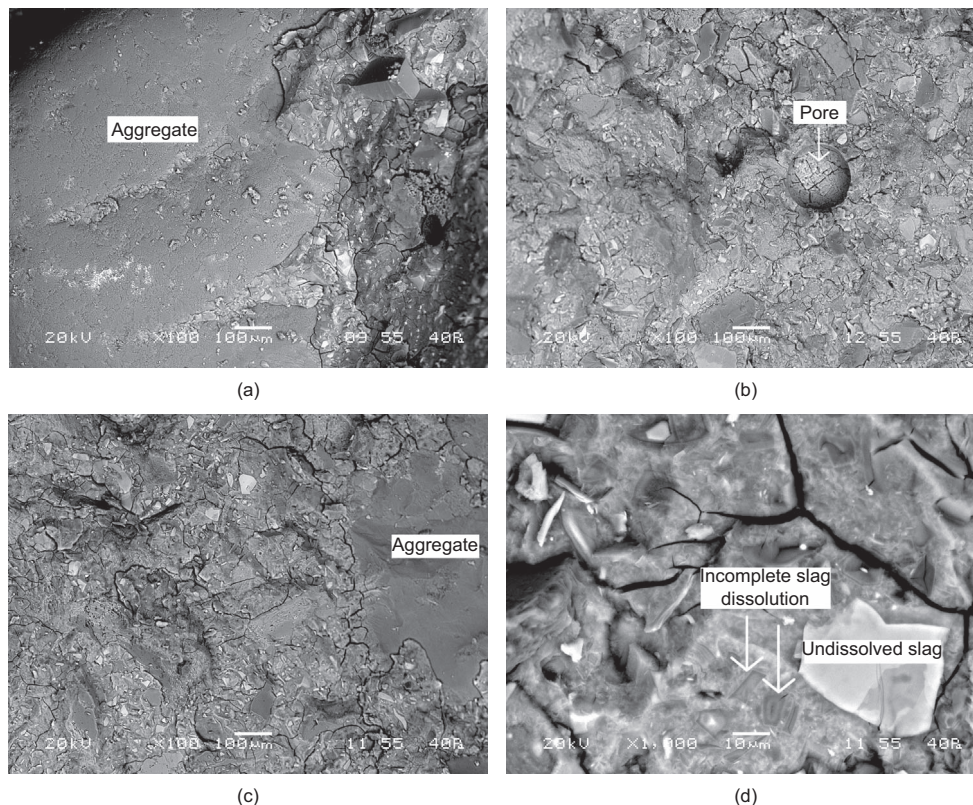


Figure 4. Compressive strength development of slag-based mortars





**Figure 5.** SEM images of the GGBS series mortars: (a) SS; (b) M; (c) and (d) CCS

possible that some of the microfissures formed due to drying shrinkage during the hardening of the mortar, it is most probable that they appeared during storage in the desiccator during sample preparation for scanning electron microscopy (SEM), as indicated previously by Palacios and Puertas (2011). The SS sample (Figure 5(a)) has thicker and more distinct microfissures than the samples with higher water content, M and CCS (Figures 5(b) and 5(c)). The more rough particle surface for the CCS compared with the SS (Figures 5(c) and 5(a)) provides an explanation as to why a higher water content was required with the CCS to achieve a similar workability to the SS. Figure 5(d) shows the CCS mix and illustrates in high magnification the vitreous nature of the matrix, while the different intensity of grey indicates the progressive dissolution of slag particles. Mica mineral particles could be detected during the SEM analysis.

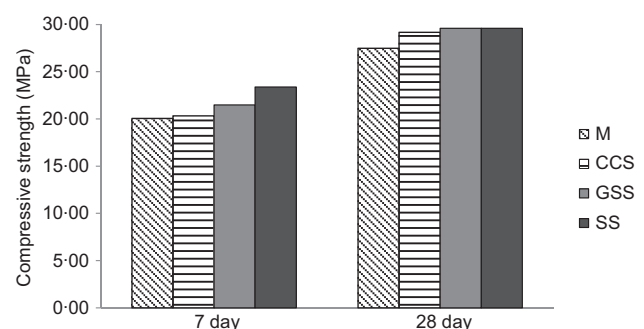
#### 4.2 PC mortars

Figure 6 shows the mixes with PC mortar. For the specific Portland-based cement used, the values of strength are of the order of 20–30 MPa. The ratio of strength between the mixes does not vary significantly on days 7 and 28. CCS performs as

well as the control mortars and M has less than 8% difference from the strongest mixes, GSS and SS, on day 28.

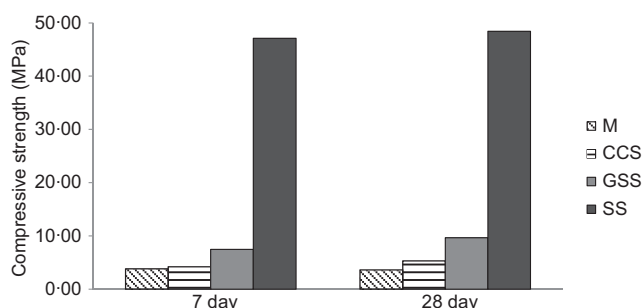
#### 4.3 FA mortars

The results of FA mortars were disappointing: the mortars on average did not gain strength over time and all apart from the SS control mortar showed extremely low performance (Figure 7). Owing to the poor performance, testing was



**Figure 6.** Compressive strength development of PC mortars



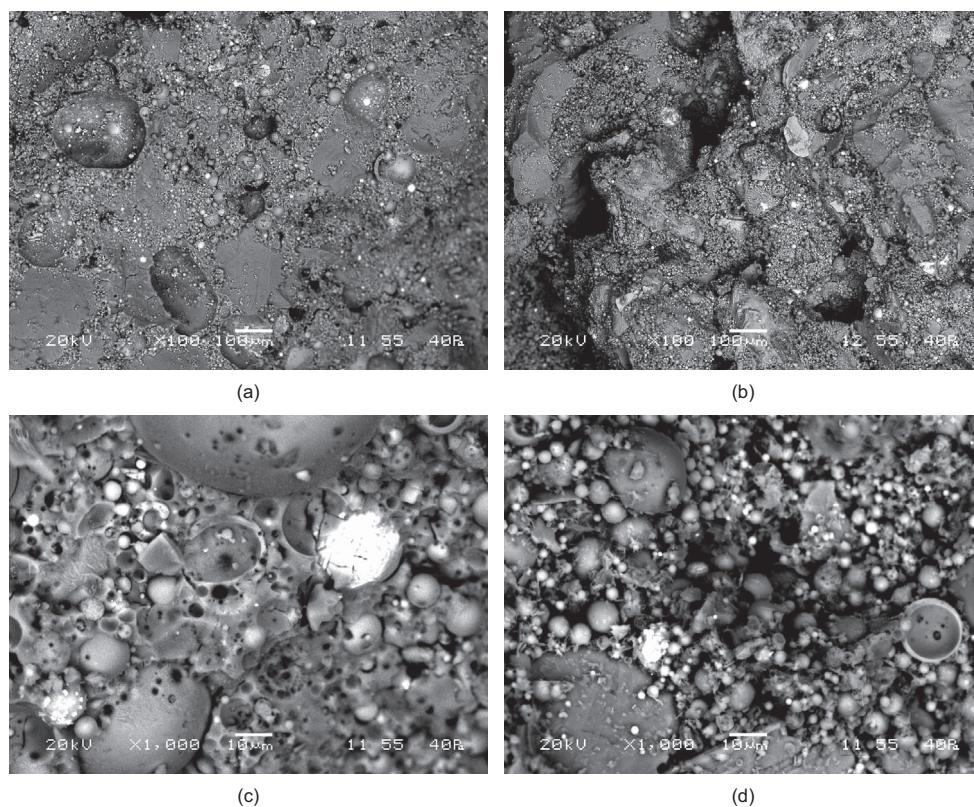


**Figure 7.** Compressive strength development of FA-based mortars

stopped after 28 d. To understand why the samples using CCS, M and GSS (with a higher water-to-binder ratio, as shown in Table 4) achieved such low strengths, the SS control mortar was repeated with an increased water content, so that the binder: water: sand ratio was 1: 0.55: 3 (not included in Table 4 and Figure 7). This produced a mix which was too fluid, and this resulted in segregation of the sand and binder, a trend which was not noted with the finer sands. The specimens were tested after 7 d and the strength was 9.66 MPa, which

indicates it is most likely the extra water required to obtain the desired workability that reduced the strength of the mortar. Therefore, without use of a water reducing admixture, a significantly higher binder:aggregate (B:A) ratio or an increased activator content, the strength of the AA FA mortar using the china clay waste cannot be improved. Increasing the activator content or B:A ratio will result in a cost and environmental impact, which would defeat the aim of the research. As a result, the research into the FA mortars was not taken any further.

Figure 8 shows images of the M and SS samples. The topography of M is not glassy; it is inhomogeneous and the aggregate can easily be detected behind the loosely structured FA particles, which show limited dissolution when used with the M sand. The binder with the SS sand is largely amorphous and dense, indicating dissolution and formation of a geopolymeric structure. The completely different nature of the binders is shown even more intensively in high magnification (Figures 8(c) and 8(d)). The lack of dissolution may be because the increased water required for the M samples resulted in a lower concentration activator, which limited dissolution, indicating the difficulty of extrapolating binder results to mortars for AA geopolymers.



**Figure 8.** SEM images of the FA series mortars: (a) and (c) show SS; (b) and (d) show M

#### 4.4 Discussion

Through the materials used (Table 1), it is not possible to effectively distinguish the effect of micas and kaolin on the strength of the mixes. Previous work by Fernandes *et al.* (2007) has shown that replacing silica sand by up to 20% kaolin has limited effect on the compressive strength of PC-based mixes. As this 20% kaolin content is much higher than that of the materials used for this paper, and as micas have been shown to affect PC-based concrete mixes at much lower contents (Fookes and Revie, 1982), this discussion has focused on the effect of mica rather than kaolin on the compressive strength of the material.

As the FA-based AA binders performed so poorly and because this was demonstrated to be related to the water-to-binder ratio, rather than the aggregate type, these mortars are excluded from this discussion. The discussion is therefore focused on the PC and AA slag (AAS) binders. For the mixes of different water content but of adjusted aggregate content (incorporating the 'volume factors'), PC binders resulted in mortars of similar strength, whereas the AA-based mortars showed greater diversity, thus justifying the initial assumptions that behaviour would be different.

Data on the effect of mica content on the compressive strength of PC-based cements were obtained from Fookes and Revie (1982) and the data on the effect of water-to-binder ratio on the compressive strength of both PC and AAS concretes were obtained from Yang *et al.* (2012). The work by Fookes and Revie (1982) represents mixes with different mica contents which have similar workability and different water-to-binder ratios as used for this study, but a limitation of the previous study by Fookes and Revie is that the binder content per unit volume was different, because the different volume factors were not accounted for. The work by Yang and co-workers was based on concrete mixes with the same volume of water per unit volume concrete, so as the water-to-binder ratio

increased, the binder content per unit volume of concrete also decreased. That previous study was also focused on calcium hydroxide/sodium silicate-based AASs, rather than the sodium hydroxide/sodium silicate-based AASs used here.

Figures 9 and 10 show the data for the present study along with that from Fookes and Revie (1982) and Yang *et al.* (2012). The data are shown as a percentage reduction in compressive strength from a reference case with no mica for each mix design. The data shown for Yang *et al.* do not include mica content, but rather represent the reduction in compressive strength as the water-to-binder ratio (Table 4) increases from the baseline case with no mica (GSS and SS for the medium-fine and medium-coarse gradings), to the case with 9% mica (CCS and M respectively).

As shown in Figure 9 for the medium-fine sand, the strength reduction with increased mica content or water-to-binder ratio for both the AAS and PC mortars is considerably lower than that indicated by the work of Fookes and Revie or Yang *et al.* This is most likely because the authors of both these previous studies varied the binder content per unit volume by not accounting for volume factors or by fixing the volume of water (rather than the volume of binder) in the mixes. As the mica flakes have a higher bulking factor than the more cubic quartz used for the ground SS (Table 4), not accounting for bulking would result in a decreased binder content per unit volume as the mica content was increased, which would lead to a reduction in strength. This demonstrates the importance of considering bulking when investigating different aggregates and of maintaining the same binder content per unit volume when considering the water-to-binder ratio. This is a particularly important consideration when attempting to manufacture low-impact PC or AAS concretes where the binder provides the greatest contribution to impact (Habert *et al.*, 2011).

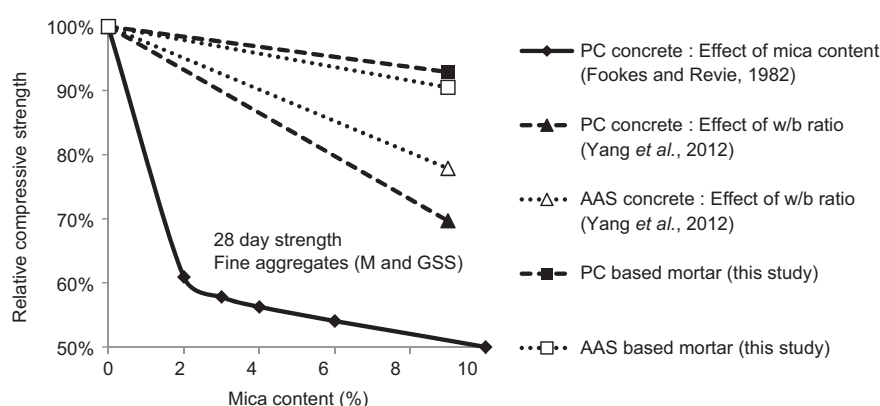
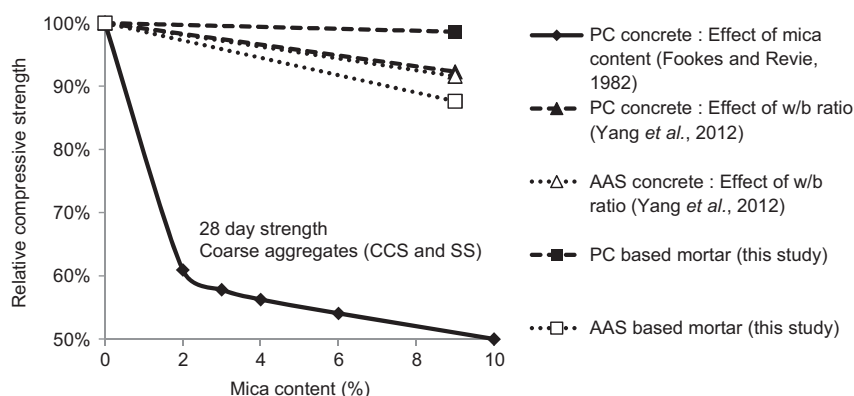


Figure 9. Reduction of strength for increasing content of mica mineral for fine materials



**Figure 10.** Reduction of strength for increasing content of mica mineral for coarse materials

As shown in Figure 10 for the medium-coarse sand, the strength reduction with increased mica content or water-to-binder ratio for both the AAS and PC mortars is again much lower than that predicted by Fookes and Revie (1982) and is generally close to or lower than the strength reduction that can be attributed to the increase in water-to-binder ratio (Yang *et al.*, 2012).

## 5. Conclusion

The high water demand of the china clay waste has a negative impact on strength for PC and geopolymer binders, but this effect varies depending on the specific mix design.

The china clay waste performed poorly with FA-based geopolymer binders and this was largely attributed to the high water content required for mixing. It is unlikely that these mixes could be used unless an effective plasticiser is incorporated in the mixture and/or the mix is redesigned for higher alkalinity or higher ratio of B:A, but this will increase environmental impacts and costs.

The use of fine china clay waste in slag-based AA cement is possible and there is potential for optimisation. The samples incorporating china clay waste initially develop strength slowly, but in the long term they tend to approach the strength of the control mortars with quartzitic sand. In particular, based on the results of compression testing after 6 months, samples with CCS of standardised particle distribution have the same strength as samples with SS. The reduction in strength with increased water content to obtain the required workability with these waste materials is not as high as expected from previous research. Although the use of the waste does result in slight strength decreases compared with the control sand, an overall environmental and cost benefit may result through use of this waste material.

Using the china clay waste with PC appears to have very little strength reduction compared to SS. This is contrary to

previous research, which indicated larger strength reductions with increasing binder contents. This previous research was based on mixes that did not account for the increase in volume for the waste material, which provided a net decrease in binder content per unit volume. This aspect of different bulking or volume factors must be accounted for if an accurate assessment of different wastes is to be undertaken.

Although the ‘mica’ waste stream is finer than materials typically used as aggregate in cementitious products, it may provide adequate strength for certain applications without the high-energy crushing process required for the production of sand from coarser china clay waste streams. The overall environmental impact of this approach and durability of these materials should be assessed before use.

## 6. Practical relevance and potential applications

This publication is the first step towards the establishment of china clay waste as an alternative type of aggregate used in AA cement, and looks at mechanical strength. While strength can provide an indication of potential suitability for use in concrete blocks and roof tiles, studies should also be conducted to assess durability. Benefits arise from the reuse of the china clay waste, the reuse of by-products such as FA and GGBS, and the low carbon dioxide emission of manufacturing AA binders. In addition, making mortar using different forms of the waste implies great variety of applications in construction and would advance the local Cornish economy. Scaling up to manufacturing of AA concrete and durability tests related to the freeze–thaw behaviour and water absorption are future goals of the research to explore potential applications.

## Acknowledgements

This research is funded by the BRE Trust. The authors would like to thank BRE for the grant and technical support and

Imerys Minerals Ltd for the time, materials, valuable comments and provision of data.

## REFERENCES

- BGS (2013) *Mineral Planning Factsheet: Construction Aggregates*. British Geological Survey, Nottingham, UK.
- Brown TJ, Walters AS, Idoine NE *et al.* (2012) *World Mineral Production: 2006–2010*. British Geological Survey, Nottingham, UK.
- BSI (1999a) BS EN 1015-2: Methods of test for mortar for masonry. Bulk sampling of mortars and preparation of test mortars. BSI, London, UK.
- BSI (1999b) BS EN 1015-3: Methods of test for mortar for masonry. Determination of consistence of fresh mortar (by flow table). BSI, London, UK.
- BSI (2002) BS EN 12620:2002+A1:2008: Aggregates for concrete. BSI, London, UK.
- BSI (2005a) BS EN 196-1: Methods of testing cement. Determination of strength. BSI, London, UK.
- BSI (2005b) BS EN 196-3: Methods of testing cement – Part 3: Determination of setting times and soundness. BSI, London, UK.
- BSI (2006) BS 8500-1:2006+A1:2012: Concrete. Complementary British Standard to BS EN 206-1. Method of specifying and guidance for the specifier. BSI, London, UK.
- BSI (2013a) BS EN 1097-6: Tests for mechanical and physical properties of aggregates. Determination of particle density and water absorption. BSI, London, UK.
- BSI (2013b) BS EN 206:2013: Concrete. Specification, performance, production and conformity. BSI, London, UK.
- Davidovits J (2011) *Geopolymer Chemistry and Applications*. Geopolymer Institute, Saint-Quentin, France.
- Dewar J (1963) *Effect of Mica in the Fine Aggregate on the Water Requirement and Strength of Concrete*. Cement and Concrete Association, Slough, UK, Technical Report TRA/370.
- Duxson P, Fernández-Jiménez A, Provis JL *et al.* (2007) Geopolymer technology: the current state of the art. *Journal of Materials Science* **42**(9): 2917–2933.
- Fernandes VA, Purnell P, Still GT and Thomas TH (2007) The effect of clay content in sands used for cementitious materials in developing countries. *Cement and Concrete Research* **37**(5): 751–758.
- Fookes PG and Revie WA (1982) Mica in concrete – a case history from Eastern Nepal. *Concrete (Journal of the Concrete Society)* **16**(3): 12–16.
- Habert G, D’Espinose de Lacaillerie JB and Roussel N (2011) An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of Cleaner Production* **19**(11): 1229–1238.
- Marsh B (2006) One Coleman street – a case study in the use of secondary materials in concrete. *Proceedings of Annual Technical Symposium on Concrete for a Sustainable Future*. The Institute of Concrete Technology, Camberley, Surrey, UK.
- Marsh B (2007) One Coleman Street – a case study in the use of secondary materials in concrete. *The Structural Engineer* **85**(9): 35–37.
- Metz B (2007) *Climate Change 2007: Mitigation of the Climate Change*. Intergovernmental Panel on Climate Change, Cambridge, UK, contribution of working group III to the Fourth Assessment Report.
- Oelkers EH, Schott J, Gauthier JM and Herrero-Roncal T (2008) An experimental study of the dissolution mechanism and rates of muscovite. *Geochimica et Cosmochimica Acta* **72**(20): 4948–4961.
- Palacios M and Puertas F (2011) Effectiveness of mixing 237–238 time on hardened properties of waterglass-activated slag pastes and mortars. *ACI Material Journal* **108**(1): 73–78.
- Shi XS, Collins FG, Zhao XL and Wang QY (2012) Mechanical properties and microstructure analysis of fly ash geopolymeric recycled concrete. *Journal of Hazardous Materials* **(0)**: 20–29.
- Sims I and Brown B (2003) Concrete aggregates. In *Lea’s Chemistry of Cement and Concrete* (Hewlett PC (ed.)), 4th edn. Butterworth-Heinemann, Oxford, UK, ch. 16, pp. 907–1015.
- Thurlow C (2005) *China Clay from Cornwall and Devon – The Modern China Clay Industry*. Cornish Hillside Publications, St Austell, UK.
- Wrap (2004) *Use of China Clay Sand as Fine Aggregate in Pre-mixed Concrete Structural and Non-Structural Applications*. Wrap, Banbury, Oxfordshire, UK, see [http://aggregain.wrap.org.uk/case\\_studies/2676\\_use\\_of\\_chin.html](http://aggregain.wrap.org.uk/case_studies/2676_use_of_chin.html) (accessed 16/08/2013).
- Yang KH, Cho AR and Song JK (2012) Effect of water–binder ratio on the mechanical properties of calcium hydroxide-based alkali-activated slag concrete. *Construction and Building Materials* **29**: 504–511.

## WHAT DO YOU THINK?

To discuss this paper, please email up to 500 words to the editor at [journals@ice.org.uk](mailto:journals@ice.org.uk). Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.

*Proceedings* journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via [www.icevirtuallibrary.com/content/journals](http://www.icevirtuallibrary.com/content/journals), where you will also find detailed author guidelines.